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January 2004

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Introduction

As operating temperatures of gas turbine engines continue to increase, there is a need for superalloy turbine disks which can operate with rim temperatures in excess of 1300 ºF. To obtain this goal, a new generation of nickel-base superalloys, such as ME3, Alloy 10, and LSHR (ref. 1 to 3), have been developed. These alloys are all strengthened by a high volume fraction of the ordered intermetallic precipitate, Ni_3Al. Although they provide advantages over older alloys, the continuing need for high tensile strength in the bore, which runs much cooler than the rim, as well as high creep strength in the rim also demands innovative heat treatments which can optimize bore and rim properties. Traditional solution heat treatments produce fine grain disks when solution temperatures are maintained below the Ni_3Al solvus or coarse grain disks when the solution temperature is maintained above the Ni_3Al solvus. Recently, several advanced solution heat treatment technologies (ref. 4 to 6) have been developed which can produce superalloy disks with fine grain bores, for high tensile strength at intermediate temperatures, and coarse grain rims, for high creep strength at elevated temperatures, by differential heating of the bore and rim. Coupon testing has demonstrated the advantages of a fine grain bore and coarse grain rim for disks produced using these advanced solution heat treatment technologies, including a low cost, Dual Microstructure Heat Treatment (DMHT) technology developed by NASA (ref. 7).

In this study, high temperature burst testing of a DMHT disk will be run to verify the integrity of the transition zone using an advanced nickel-base superalloy, LSHR. The burst data will also be analyzed using finite element methods to obtain an understanding of the deformation characteristics of the DMHT disk during the burst event.

Materials and Procedures

Superalloy disks of LSHR alloy were used in this study. LSHR powder of the composition shown in table 1 was produced by argon atomization. The powder was then screened, canned, compacted and extruded to 6 in. diameter billet. The billet was subsequently cut to mults and isothermally forged to a cylindrical shape 12 in. diameter and 2 in. thick. The forgings were then machined to the shape shown in figure 1 for heat treatment.

Two forgings, one for coupon testing and the other for burst testing, were heat treated to develop a dual grain structure using the NASA DMHT process. The forgings were given a pre-solution heat treatment at 2075 ºF before the DMHT step to develop a uniform, ASTM 12 grain size from bore to rim. The DMHT process is fully described in ref. 6 but is summarized here for the reader's convenience. The basic concept behind the DMHT process utilizes the thermal gradients between the interior and exterior of the forging during the initial phases of a conventional solution heat treatment to develop a dual grain structure. By enhancing these thermal gradients with heat sinks, it is possible to design a solution heat treatment which can produce the desired dual grain structure. The heat sinks are solid metal cylinders, termed thermal blocks, which chill the central portion of the forging. Two thermal bocks are generally utilized, one on the top face and one on the bottom face of the forging as shown in figure 2. To enhance the effectiveness of the thermal blocks an insulating jacket can be employed to slow the temperature rise of the thermal blocks and the central portion of the forging. A thermocouple is embedded in one of the thermal blocks to monitor temperature near the center of the forging. The entire assembly, forging and heat sinks, is placed into a standard gas-fired furnace maintained at a temperature above the solvus of the alloy, in this case 2175 ºF. The entire assembly is removed from the furnace when the outer periphery of the forging has exceeded the solvus but before the central portion of the forging reaches the solvus, thereby producing the dual grain structure. In this instance the time in the furnace was about one hour. Upon removal of the assembly from the furnace, the forging and heat sinks are rapidly separated and the forging is cooled as required. In this study the forgings were quenched in agitated oil with a transfer time from furnace to quench tank of 45 seconds. Finally, the forgings were aged at 1500 ºF for eight hours to stabilize the Ni_3Al precipitates and carbides.

The first forging was machined to the configuration shown in figure 3 for spin testing to burst at 1300 ºF. This design was developed to produce a uniformly high stress region in the web of the disk while minimizing the stress in the bore. This philosophy maximizes the deformation in the web, which encompasses the grain size transition zone of the DMHT disk. The 1300 ºF test temperature was selected as it typifies anticipated disk operating temperature at the transition zone in advanced engine designs. The second forging was used to obtain tensile coupons for testing at 1300 ºF to support finite element analysis of the burst trial. The cutup plan for the second forging is shown in figure 4.

The spin testing in this study was performed using facilities of the Balancing Company located in Dayton, Ohio. The spin pit employed an air turbine drive, electrically heated furnace, and a high temperature arbor shown in figure 5. The arbor design utilized two clamping mechanisms to hold the disk as seen in figure 6. The primary clamping mechanism employed a 9 in. stretch bolt, while a secondary clamping mechanism was provided by capture flanges. In this design, the clamping force exerted by the capture flanges increases as the disk grows in a radial direction and therefore tends to counteract any decrease in clamping force by the stretch bolt as the disk shrinks in the axial direction. The burst test was run in several segments so radial growth of the disk could be measured and compared to finite element predictions. The disk was spun to speeds of 35 000, 38 000, and 40 000 rpm before running to failure. After each of the first three trials the disk was cooled and removed from the pit to measure radial growth. To minimize creep in each of these trials the speed was increased at a rate of 5000 rpm every minute.

Results and Discussion

A dual grain structure was successfully produced in the two LSHR disks used in this study. The bore had a fine grain size, about ASTM 12, while the rim had a coarse grain size, about ASTM 5. The transition zone was located about 2 in. from the outer periphery of the disk. This structural transition is shown in the macrosection presented in figure 7.

Tensile test data is presented in table 2. The fine grain bore is seen to have a higher yield strength than the coarse grain rim at 1300 ºF; however, the ultimate tensile strength is similar, running around 200 ksi for both bore and rim. Further, transition tensile data showed strength and ductility levels which were within the range for bore and rim data.

The spin testing of the DMHT disk proceeded without incident. The first three trials to 35 000, 38 000, and 40 000 rpm produced increasing degrees of plastic growth of the disk as documented in table 3. On the fourth spin trial the disk burst at a speed of 42 530 rpm. As seen in figure 8, the failure location was about one inch from the outer periphery of the disk, placing it in the coarse grain region. A typical region of the fracture surface is presented in figure 9, and shows features generally associated with ductile failure.

Finite element analysis of the spin testing was performed using a 2–D axisymmetric model shown in figure 10. Two material groups were employed, fine grain and coarse grain. In both cases a bilinear, elastic-plastic material response was assumed with an elastic moduli of 26 000 ksi and a plastic moduli of 600 ksi. The yield stress for the fine grain and coarse grain material were 170 and 160 ksi respectively. Analyses were run at 35 000, 38 000, 40 000, and 42 000 rpm. As the stress state is multiaxial the magnitude of the von Mises stress was examined. At 42 000 rpm the peak stress reached 200 ksi in the web, as shown in figure 11. The disk would be expected to burst at this speed as the ultimate tensile strength of the alloy has been reached. To verify the accuracy of the stress distributions, the predicted growth of the disk is compared with experimentally measured growth of the disk in figure 12. In general, the comparison is quite good thereby verifying the accuracy of the stress distribution in figure 11.

From this test, one would conclude that the DMHT disk, in general, and the transition zone, in particular, met or exceeded the expectation for several reasons. First, the disk failed near the predicted speed. Second, significant growth of the disk occurred before failure. Lastly, the fracture appeared to be ductile in nature.

Summary and Conclusions

Elevated temperature burst testing of a disk with a dual grain structure made from an advanced nickel-base superalloy, LSHR, was conducted. The disk had a fine grain bore and coarse grain rim, produced using NASA's low cost DMHT technology. The results of the spin testing showed the disk burst at 42 530 rpm in line with predictions based on a 2–D finite element analysis. Further, significant growth of the disk was observed before failure which was also in line with predictions.

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7. J. Gayda and D. Furrer, "Dual Microstructure Heat Treatment", Advanced Materials & Processes, July 2003.

TABLE 1.—COMPOSITION OF LSHR ALLOY IN W/O

Co	Cr	Al	Ti	W	Mo	Nb	Ta	C	B	Zr	Ni
20.8	12.7	3.48	3.47	4.37	2.74	1.45	1.65	0.024	0.028	0.049	Bal.

TABLE 2.—1300 ºF TENSILE DATA
H1 thru H8 are of hoop orientation from bore to rim respectively.
R9 and R10 are of radial orientation thru the transition zone.

Specimen	UTS, ksi	0.2 % yield, ksi	Elongation, percent	RA, percent
H1	198	175	4.3	7.0
H2	192	170	3.9	8.0
H3	199	172	6.5	8.0
H4	196	170	8.0	13.0
H5	199	173	4.2	7.5
H6	202	164	7.0	8.5
H7	203	160	7.0	9.0
H8	193	157	6.5	10.0
R9	202	166	5.5	6.5
R10	202	167	5.5	6.5

TABLE 3.—MEASURED DIAMETER OF DISK
AFTER SPINNING TO INDICATED SPEED

Max speed, rpm	Diameter, inches
0	11.696
35 000	11.708
38 000	11.722
40 000	11.733
42 530	Burst

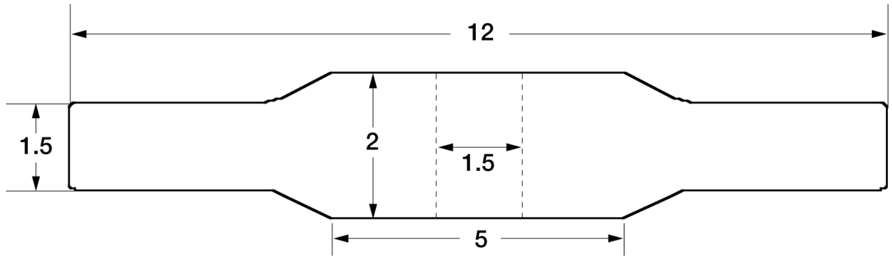

Figure 1.—Machining plan for heat treat shape. All dimensions are in inches.

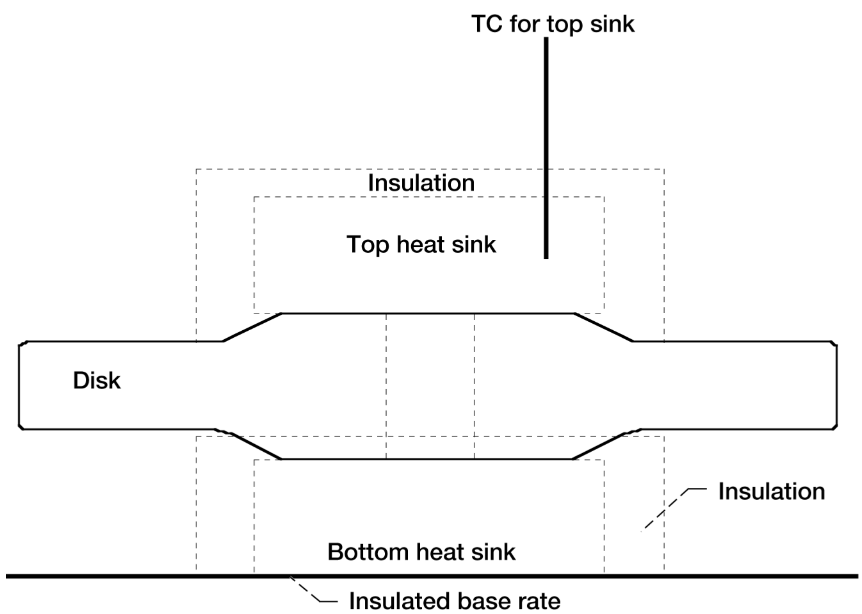

Figure 2.—Disk and heat sinks used in DMHT conversion.

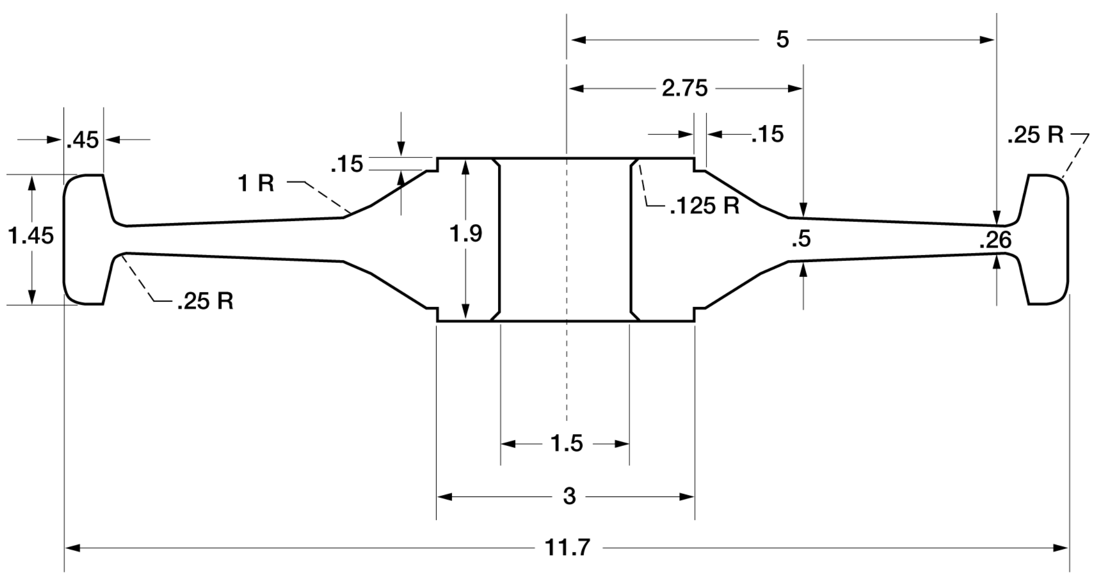

Figure 3.—Machining plan for spin disk. All dimensions are in inches.

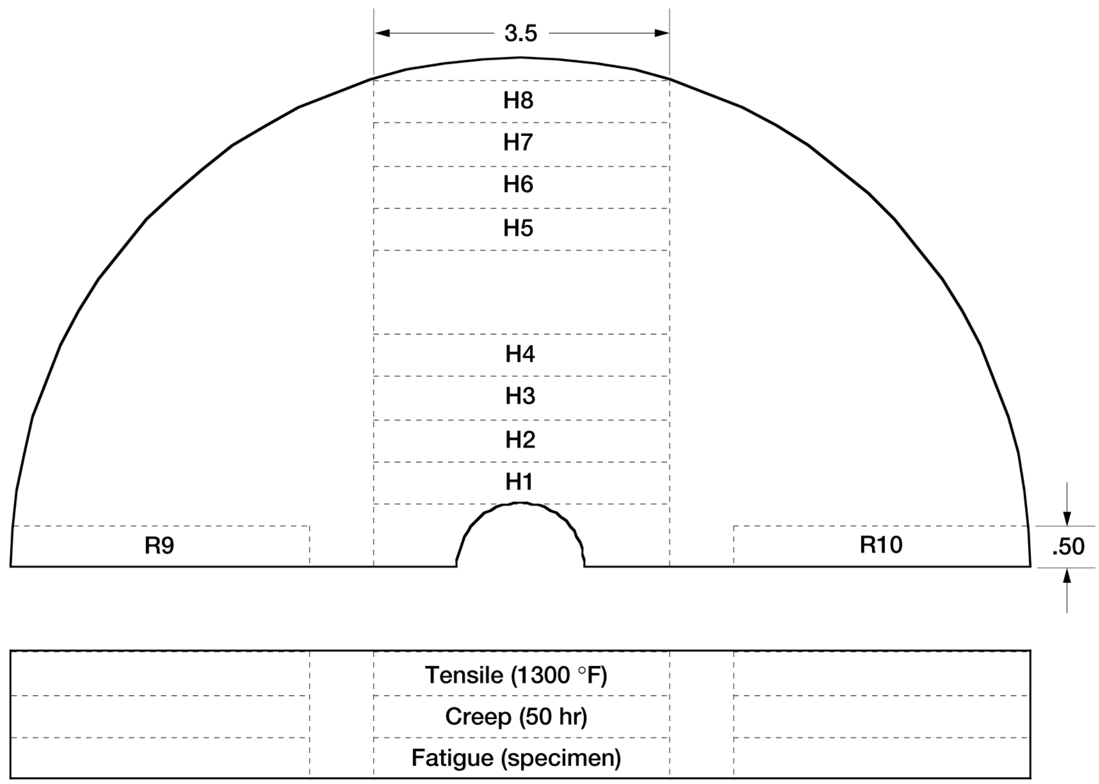

Figure 4.—Cut up plan for tensile testing. Only half the forging was used.

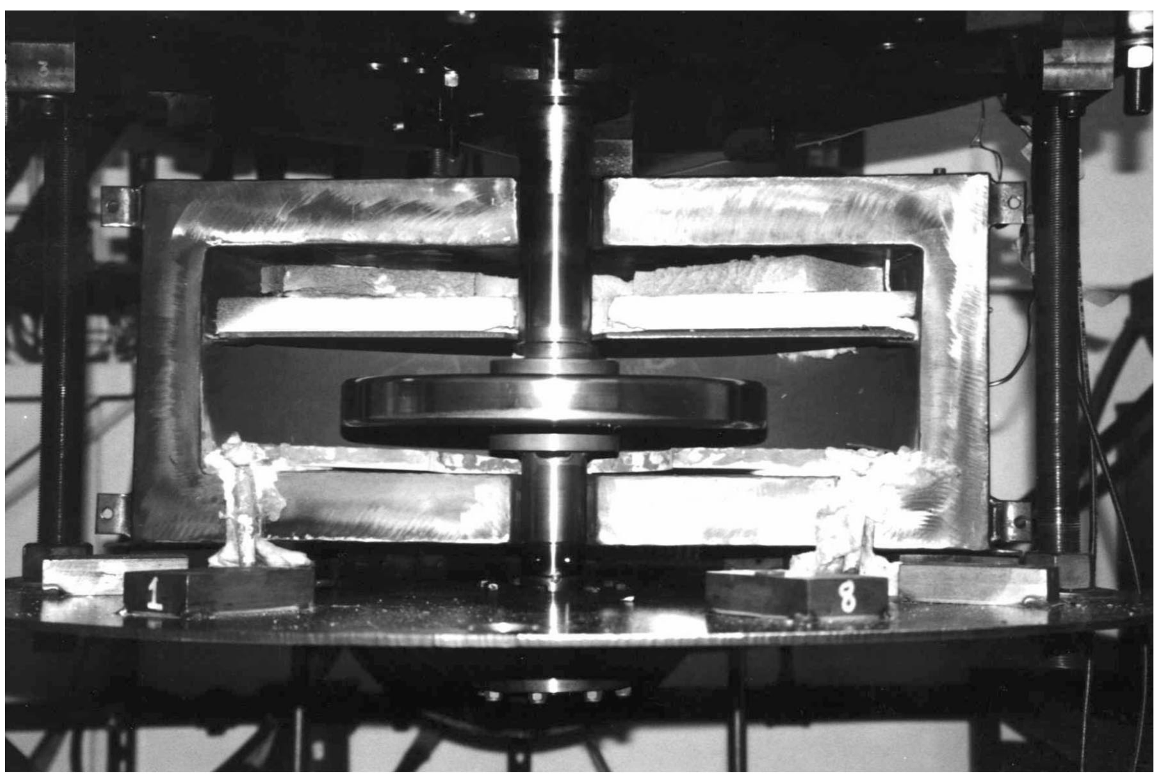

Figure 5.—Photo showing disk, arbor, and half of furnace used for spin testing.

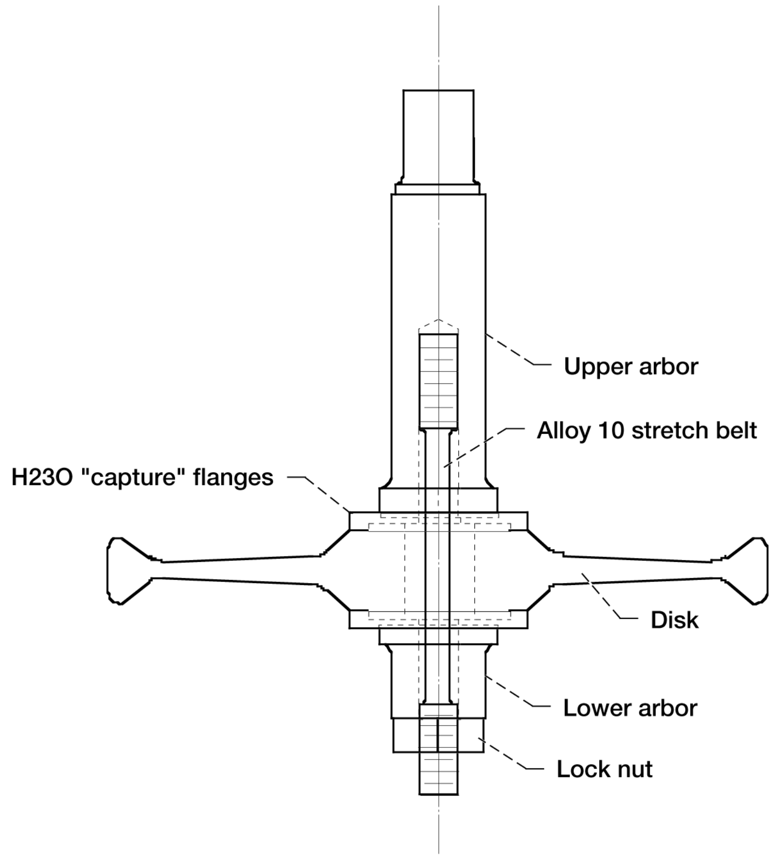

Figure 6.—Design of high temperature arbor.

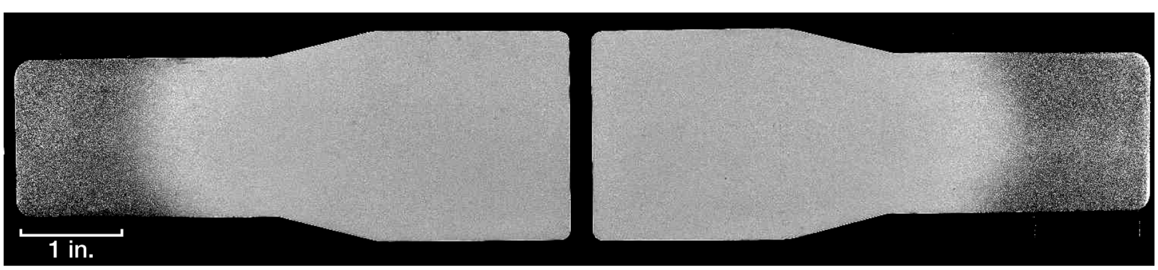

Figure 7.—Macrosection of DMHT forging showing grain size transition.

Figure 8.—Selected fragments from disk burst.

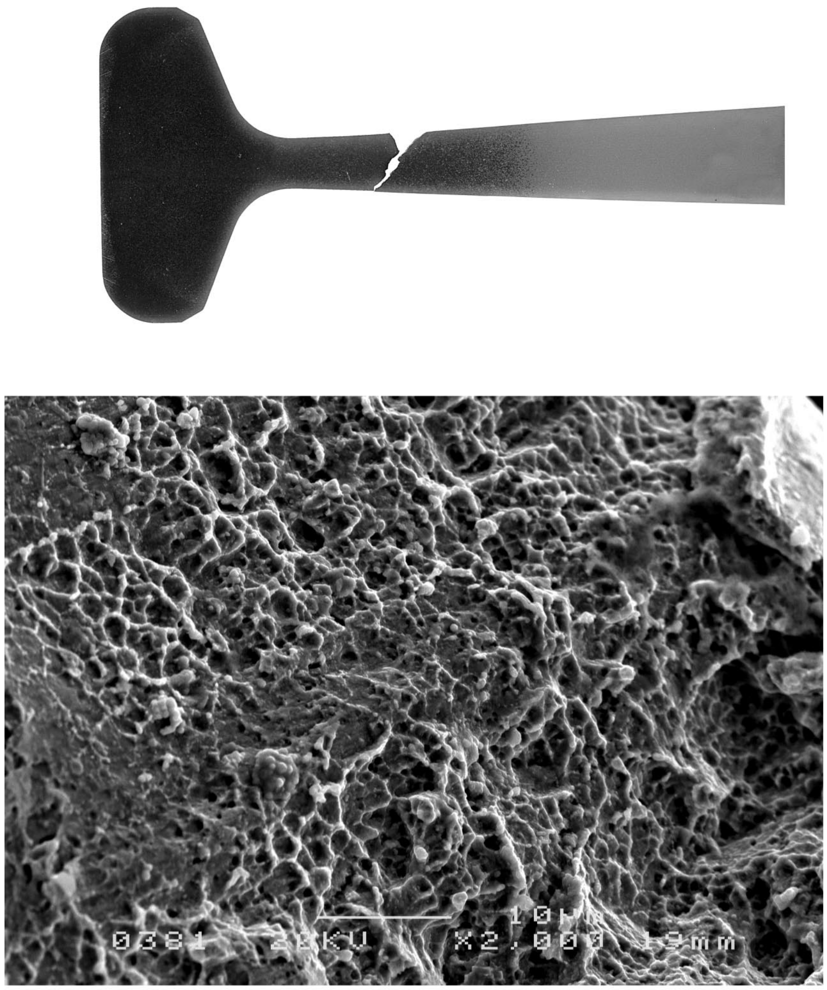

Figure 9.—View of disk fracture showing position relative to grain size transition (top) and ductile morphology of fracture surface (bottom).

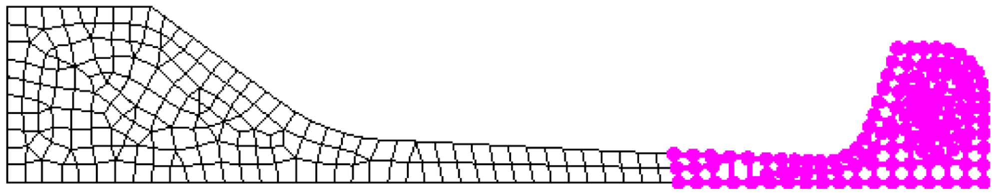

Figure 10.—2-D axisymmetric finite element model showing fine grain and coarse grain material groups.

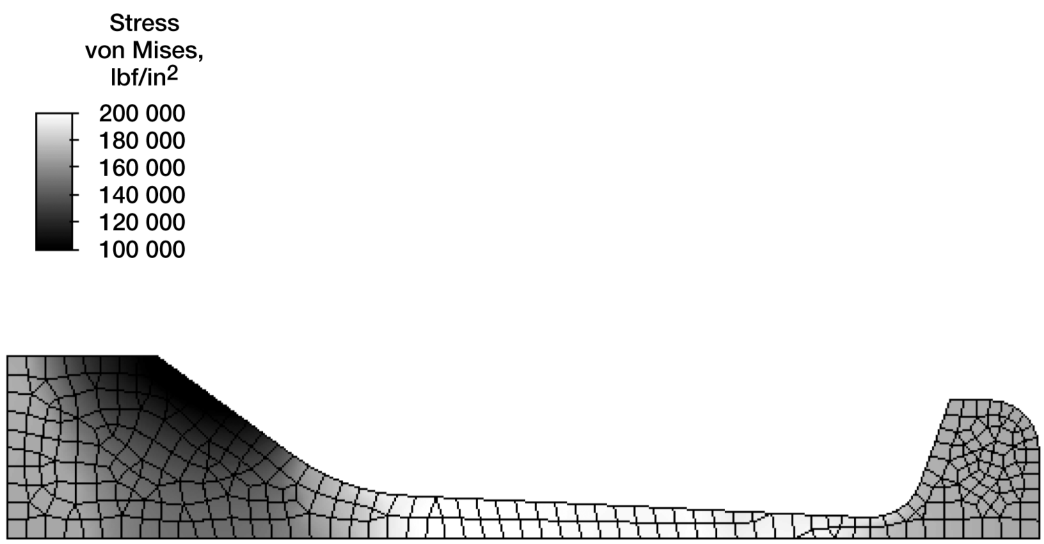

Figure 11.—Stress distribution at 42 000 rpm.

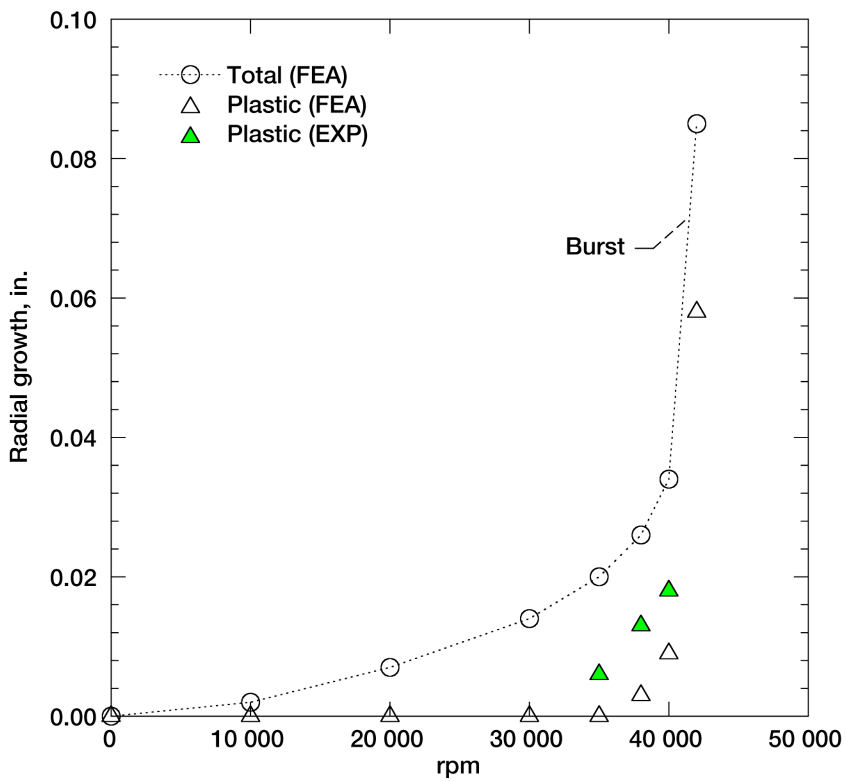

Figure 12.—Comparison of predicted (FEA) and measured (EXP) growth of disk during spin testing at 1300 °F.

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